RADIATION DAMAGE IN THE SILICON DIOXIDE (SIO_2) LAYER

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ABSTRACT

The most sensitive part of a metal–oxide–semiconductor (MOS) structure to ionizing radiation is the oxide insulating layer. When ionizing radiation passes through the oxide, the energy deposited creates electron/hole pairs. Oxide trapped charge causes a negative shift in capacitance-voltage (C-V) characteristics. These changes are the results of, firstly, incre asing trapped positive charge in the oxide, which causes a parallel shift of the curve to more negative voltages, and secondly, increasing interface trap density, which causes the curve to stretch-out.

ABSTRAK

The most sensitive part of a metal–oxide–semiconductor (MOS) structure to ionizing radiation is the oxide insulating layer. When ionizing radiation passes through the oxide, the energy deposited creates electron/hole pairs. Oxide trapped charge causes a negative shift in capacitance-voltage (C-V) characteristics. These changes are the results of, firstly, increasing trapped positive charge in the oxide, which causes a parallel shift of the curve to more negative voltages, and secondly, increasing interface trap density, which causes the curve to stretch-out.

Keywords: ionizing, MOS, radiation damage, silicon dioxide (SiO_2)

INTRODUCTION

The radiation damage in the silicon dioxide (SiO_2) layers consists of three components: the buildup of trapped charge in the oxide, an increase in the number of interface traps, and an increase in the number of bulk oxide traps (Oldham and McLean, 2003; Haider and Abdulah, 2009). Electrons and holes are created within the SiO_2 by the ionizing radiation or may be injected into the SiO_2 by internal photoemission from the contacts. These carriers can recombine within the oxide or transport through the oxide. Electrons are very mobile in SiO_2 and move quickly to the contacts (Tamaki *et al., 2009)*; in contrast the holes have a very low effective mobility and transport via a complicated stochastic trap-hopping process (Li and Nathan, 2004). Some of these holes may be trapped within the oxide, leading to a net positive charge. Others may move to the SiO_2/Si interface, where they capture electrons and create an interface trap. Along with the electron-hole generation process, chemical bonds in the SiO_2 structure may be broken (Street, 2005). Some of these bonds may reform when the electrons and holes recombine, whereas others may remain broken and give rise to electrically active defects. These defects can then serve as interface traps, or trap sites for carriers.

Bonds associated with hydrogen or hydroxyl groups can release these impurities when broken, which are then mobile within the SiO_2. These impurities may then migrate to the SiO_2/Si interface, where they undergo a reaction which results in an interface trap. The defects created by the radiation may themselves migrate in the strained region near the SiO_2/Si interface and also result in the formation of an interface trap. Typically the net charge trapped in the oxide layer after irradiation is positive. The interface traps can exchange charge freely with the silicon substrate, and thus their charge state depends upon the bias applied to the device, it is more negative for a positive bias applied to the gate electrode than a negative bias. The energy band diagram of an MOS structure under positive gate bias is as shown in Fig. 1. There are three possible oxide trap locations.

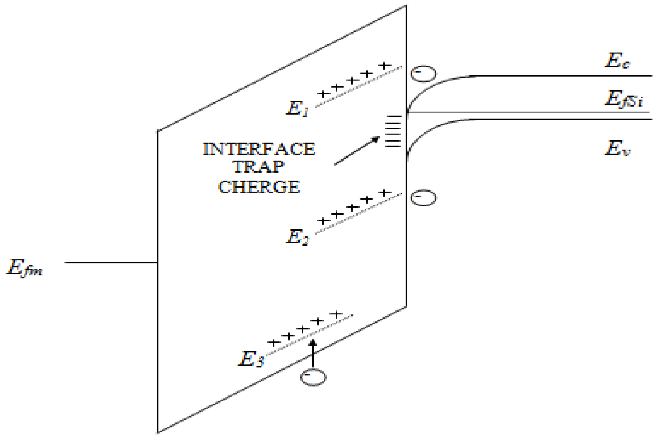

Figure 1. Energy band diagram of a MOS structure under positive gate bias

RADIATION TEST PROCEDURE

To study the radiation damage in the SiO_2 layer, 14 MeV neutrons produced from the deuterium-tritium (D-T) nuclear fusion reaction was utilized. Fusion reactions are highly exothermic reactions, usually between light nuclei, such as the isotopes of hydrogen, viz., deuterium (D=2H) and tritium (T=3H). The high voltage power supplies used Felici type high-voltage multipliers for accelerating light nuclei induced reaction (IAEA, 1996; Pereda *et al.*, 2008). The low voltage (100 kV) neutron generators produced neutrons through the following reaction, $^{2}H + {}^{3}H \rightarrow {}^{4}_{2}He + n$ (Q = 17.6 MeV) or can be written as $^{3}H(d,n)^{4}He$.

The ^{4}He and n share 17.6 MeV consistent with linear momentum conservation, and a monoenergetic neutron with energy 14 MeV emerges. This reaction often serves as a source of fast neutrons. The parameters of SAMES J-25 as a 14 MeV neutron source are listed in Table 1.

Table 1. Parameters of Generator Neutron Type SAMES J-25.

Beam energy	150 KeV (optimal)
D^+ Beam current at fix target	1.50 mA
Min. beam spot size at the target	3.10 cm
D-T neutron yield, continuously	3×10^9 n/s (optimal)
Target life (half value of neutron yield)	200 mAh. (expected)

More than 25 GF4936 dual n-channel depletion mode MOS samples were irradiated at room temperature with D-T neutrons to examine the neutron induced changes in the SiO2 of the MOS devices. All samples were set and tested around the target at different angles, that is, (0o, 15o, 30o, 60o, and 90o). The differences in angles were related to the total fluence of the neutron radiation received and its energy. Fig.2 shows the location of sample during neutron irradiation.

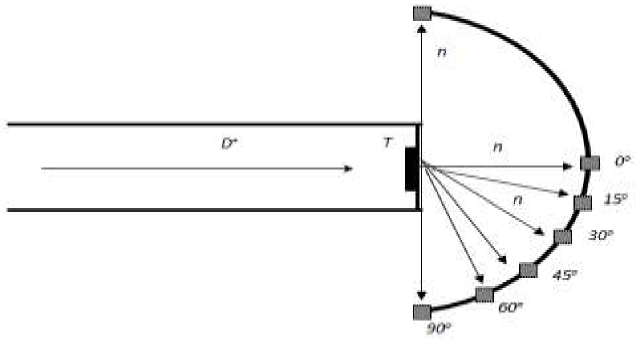

Figure 2. Location of sample toward neutron radiation.

Each irradiation of samples was performed twice; first to measure the output characteristics, and second to measure the forward transfer characteristics. In output characteristics, the gate-source voltage, VGS, was changed from +0.5 to -1.5 volts by changing the applied DC supply voltage, Vcc, starting from 0 to 20 volts. On the other hand, the characterization of MOS in order to determine the forward transfer characteristics of the gate-source voltage, VGS, was changed from –5.0 to +5.0 volts with Vcc constant of 20 volts during irradiation time.

RESULTS AND DISCUSSION

While the holes generated under exposure to ionizing radiation, travel through the oxide, MOS structures typically exhibit a negative voltage shift, ΔV_{ot}, that is not sensitive to silicon surface potential and that can persist for hours to years. This long-lived radiation effect component is the most commonly observed form of radiation damage in MOS devices and is attributed to the long-term trapping of net positive charge in the oxide layer as shown in Fig. 3. This effect generally dominates other radiation damage processes in MOS structures, including negative charge (electron) trapping and interface trap buildup effect, unless specific device-processing changes are made to alter the oxide and consequently reduce the positive charge trapping or enhance the other effects.

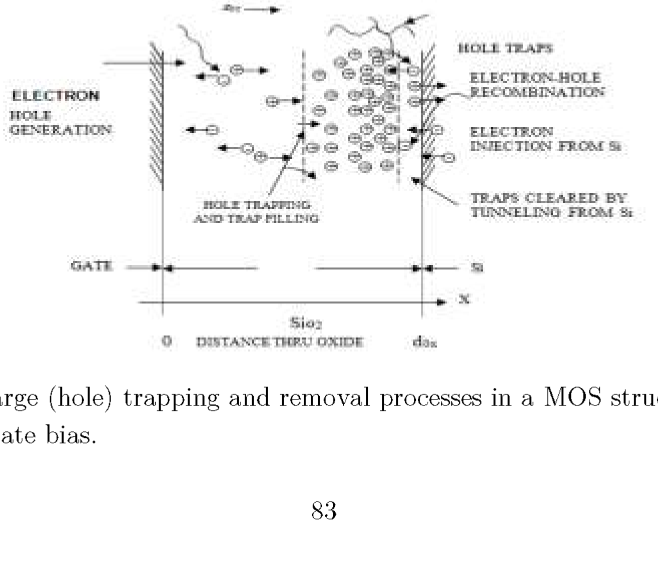

Figure 3. Oxide charge (hole) trapping and removal processes in a MOS structure under positive gate bias.

Most of the holes that are captured by hole traps within a certain distance of the silicon (2-5 nm) are believed to undergo a tunneling process (tunnel anneal) and are removed gradually, this process is thought to be primarily responsible for the "long-term annealing" of ΔV_{ot}. Meanwhile, electrons that are generated in the oxide within the trapped-hole distribution, or between the trapped-hole distribution and the silicon, swept through trapped-hole distribution. Depending upon the local density of trapped holes, n_{ht} and the cross-section for capture of an electron by a trapped hole, σ_r some of the electrons recombine with a portion of the trapped holes. Another possible process is of free electrons with free holes in the bulk of the oxide. This process is distinct from germinate or columnar recombination of electrons and holes during the charge generation process, and is not significant at reasonably attainable charge generation (dose) rates. The hole generation and trapping processes produce the buildup of ΔV_{ot} under irradiation; the electron/trapped-hole recombination and hole anneal processes tend to limit or reduce $\Delta V_{ot.}$ The overall charge buildup process (neglecting hole-removal processes other than recombination) can be expressed in the following incremental form (Arora, 2007):

$$\Delta n_{ht}\ (x, \Delta D) = F_h(x)\sigma ht\ (\ \xi_{ox}(x()[N_{ht}\ (x) - n_{ht}\ (x)] - F_e\ (x)\sigma_r\ \xi_{ox}(x))n_{ht}(x)\,. \tag{1}$$

where

n_{ht} is the local density of trapped holes

N_{ht} is the local density of hole traps

σ_r is the local oxide field-dependent cross-section for recombination of an electron with a trapped hole

F_h and F_e are the local fluences per unit dose for radiation generated holes and electrons, depend upon the "upstream" generation and removal of holes and electrons in the oxide

TheΔV_{ot} V_{ot} that results from the trapped holes is given by

$$V_{ot} = -(q/\in_{ox})\ d_{ox}\Delta N_{ot}\,. \tag{2}$$

where ΔN_{ot} $\Delta N_{ot}$is the areal charge density referred to the SiO_2/Si interface and is given in turn by

$$\Delta N_{ot} = \frac{1}{d_{ox}}\int_0^{d_{ox}} n_{ht}(x)xdx. \tag{3}$$

Under the assumption that holes trapping takes place very close to the SiO_2/Si interface in an MOS structure irradiated under positive bias. The efficiency of hole captured by the traps is a function of the electric field in the oxide. Another important parameter is the cross-section, σ_r, for capture of a free electron by a hole in the hole trap. The process of electron/hole recombination via the hole traps plays a major role in the limitation of hole trapping at higher doses (Oldham and McLean, 2003).

The holes created and trapped in deep traps in SiO_2 layer of a MOS structure after irradiations are not truly "permanently" trapped. Instead, they are observed to disappear from the oxide over times from milliseconds to years. This discharge of the hole traps, as commonly observed at or near room temperature, is the major contributor to the so-called long-term annealing of radiation damage in MOS devices. The annealing of the trapped holes has two manifestations that may reflect different hole-removal processes. The first is the slow bias-dependent recovery of ΔV_{ot} typically observed at normal device operating temperatures (-55° to 125°C, for instance). The second is the relatively rapid and strongly temperature-dependent removal or recombination of the holes observed when MOS structures are deliberately subjected to thermal annealing cycles at elevated temperatures (150° to 350°C).

The electrons generated by irradiation are much more than holes, and they are swept out of the oxide in times typically in the region of 1 ps. However, in that first picosecond, some fraction of the electrons and holes will recombine. This fraction depends greatly on the applied field and the energy and the type of incident particle.

The holes that escape initial recombination are relatively immobile and remain behind near their point of generation, causing negative voltage shifts in the electrical characteristics of MOS devices. However, over a period of extended time at room temperature, the holes undergo a rather anomalous stochastic hopping transport through the oxide in response to any electric fields present. This 'hole transport' process, which is very dispersive in time, gives rise to a short term, transient recovery in the voltage shift. It is sensitive to many variables including primarily applied field, temperature, and oxide thickness (Oldham, 2011). When the holes reach the SiO_2 interface (for positive applied gate bias), some of them are captured in long term trapping sites, and cause a remnant negative voltage shift.

Ionizing radiation induced positive charges (holes) in the insulator SiO_2, will then require a greater negative voltage to compensate the positive charge to achieve surface inversion, and thus the increase in transistor's turn-on voltage, or threshold voltage. Fig. 4 shows the kinds of changes that occurred in threshold voltage for *n*-channel and *p*-channel transistor biased either "on" or "off" during irradiation.

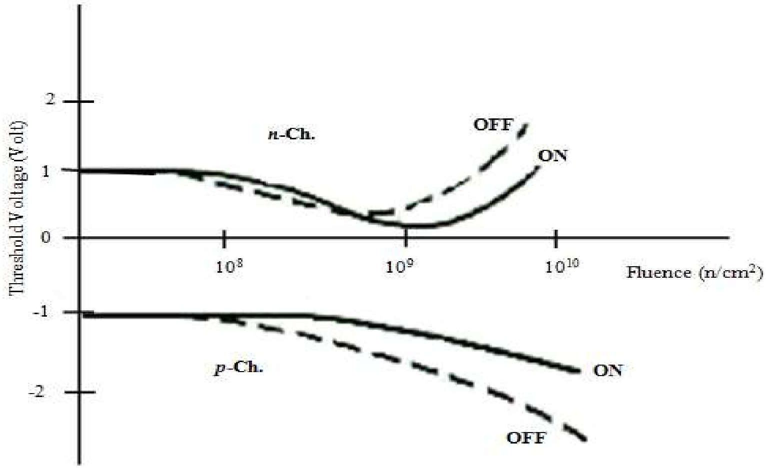

Figure 4. The changes of the threshold voltages of *n*- and *p*-channel MOS transistors as a function of fluence.

For the purpose of calculating the linear energy transfer (LET) in the device when θ = 0°, the following relationship is used; $LET = E(\text{MeV})/\rho s$ (Chee *et al.*, 2009), where ρ is the silicon density (2.33×10^3 mg/cm^3) and *s* is the tack length of energy deposited by the incident particle (1 pC/μm), thus, the LET = 96.57 MeVcm^2/mg. In order to calculate the LET at different angles, the following relationship is used; LET = $E(\text{MeV})\cos\theta/c\rho$, where *c* is the device thickness (1 micron), and the results are 92.7, 83.04, and 57.93 MeVcm^2/mg at 15°, 30°, and 60° angles of projection respectively. The vertical penetration induced the smallest energy deposition. In contrast, the horizontal penetration gave the largest energy deposition. It has been estimated that the level of displaced atoms expelled from lattice position, the microscopic total cross section for 14-MeV neutrons in silicon is $\sigma_D \approx 4.8\,\text{barn}$. The corresponding neutron mean free path, λ is given in turn by

$$\lambda = (N\sigma_D)^{-1} = (5\times10^{22}\times4.8\times10^{-24})^{-1} \approx 4\text{cm}. \quad (4)$$

This can be interpreted as the probability that an individual incident neutron produces one primary per cm is equal to 1/4. The number of primaries then produced per cm^3 is $\phi_n/4$. Each primary yields about 500 total displacements, so that $\bar{n}_s \cong 500$. Then, for a different fluence, the mean number of displaced atoms per cm^3, N_d is shown on Table 2, Table 3, Table 4, Table 5 and Table 6 respectively at the incidence angle of 0°, 15°, 30°, 60°, and 90° respectively.

Table 2. The mean number of displaced atoms per cm^3 at the incidence angle of 0°.

	Fluence (n/cm^2)	N_d ($atoms/cm^3$)
	0.66×10^{10}	0.82×10^{12}
	1.32×10^{10}	1.65×10^{12}
	1.98×10^{10}	2.47×10^{12}
	2.64×10^{10}	3.30×10^{12}
	3.31×10^{10}	4.10×10^{12}
Ave.	1.98×10^{10}	2.46×10^{12}

Table 3. The mean number of displaced atoms per cm^3 at the incidence angle of 15°.

	Fluence (n/cm^2)	N_d ($atoms/cm^3$)
	0.39×10^{10}	0.48×10^{12}
	0.78×10^{10}	0.97×10^{12}
	1.16×10^{10}	1.45×10^{12}
	1.55×10^{10}	1.93×10^{12}
	1.90×10^{10}	2.30×10^{12}
Ave.	1.15×10^{10}	1.42×10^{12}

Table 4. The mean number of displaced atoms per cm^3 at the incidence angle of 30°.

	Fluence (n/cm^2)	N_d ($atoms/cm^3$)
	0.75×10^{9}	0.94×10^{11}
	1.51×10^{9}	1.88×10^{11}
	2.26×10^{9}	2.82×10^{11}
	3.00×10^{9}	3.77×10^{11}
	9.78×10^{9}	4.72×10^{11}
Ave.	2.26×10^{9}	2.80×10^{11}

Table 5. The mean number of displaced atoms per cm^3 at the incidence angle of 60°.

	Fluence (n/cm^2)	N_d ($atoms/cm^3$)
	0.32×10^{9}	0.40×10^{11}
	0.64×10^{9}	0.81×10^{11}
	0.97×10^{9}	1.21×10^{11}
	1.29×10^{9}	1.61×10^{11}
	1.62×10^{9}	2.00×10^{11}
Ave.	0.96×10^{9}	1.20×10^{11}

Table 6. The mean number of displaced atoms per cm^3 at the incidence angle of 90°.

	Fluence (n/cm^2)	N_d ($atoms/cm^3$)
	1.68×10^{8}	2.10×10^{10}
	3.36×10^{8}	4.20×10^{10}
	5.00×10^{8}	6.30×10^{10}
	6.72×10^{8}	8.40×10^{10}
	8.40×10^{8}	10.00×10^{10}
Ave.	5.03×10^{8}	6.20×10^{10}

CONCLUSION

When ionizing radiation passes through the oxide, the energy deposited creates electron-hole pairs. High-energy neutron radiation deposits energy in MOSFET device via two mechanisms: trapped charge buildup in the silicon dioxide layer and also an increase in the density of trapping states at the silicon dioxide interface. The electric characteristics of the MOS structure are easily changed by charges trapped in the SiO_2 passivation layer. This means that the MOS devices are influenced more by ionization effects than displacement effects.

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